APPLICATION

FOR

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FOR

LOW-DRAG HYDRODYNAMIC SURFACES

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LOW-DRAG HYDRODYNAMIC SURFACES

This invention was made with Government support under DAAH01-96-C-R228, and DAAH01-98-C-R115 awarded by the Defense Advanced Research Projects Agency. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

This invention applies to the field of hydrodynamics, and relates to the use of gas cavities to reduce the frictional drag of hydrofoil craft, ship hulls and underwater surfaces in general.

Using cavities to reduce frictional drag is covered in U.S. Pats. No. 3,077,173 (1963) and No. 3,109,495 (1963) for base-vented and side-vented hydrofoils, U.S. Pat. No. 3,205,846 (1965) for torpedoes, and U.S. Pat. No. 6,167,829 (2001), together with a pending continuation of that patent, for submerged surfaces in general.

The reduction of frictional drag provides basic benefits: power is reduced, and fuel consumption is reduced. These benefits reduce the weight of a vessel, which further reduces power and fuel consumption compared with a fully wetted vessel designed for a given payload and range. Alternatively, vessel speed can be significantly increased with the same displacement, power, payload and range. Cost and time for payload delivery are greatly reduced by reducing drag.

The problem is how to design underwater surfaces to make full use of cavities to reduce drag. Needs exist for improved drag reduction in water craft.

SUMMARY OF THE INVENTION

A primary objective of this invention is to reduce the drag of high-speed hydrofoil craft by forming a closed gas cavity on each side of each lifting hydrofoil, forming an open cavity on each side of each support strut, and by covering at least one side of each propulsor blade with a cavity.

A preferred design is a hydrofoil craft that has one highly-swept-back v-hydrofoil in planform, supported by three swept struts, powered by two superventilating propellers wherein each drive shaft is located within a strut, and wherein the hydrofoil sweep back eliminates cavitation and reduces craft motion in waves.

Another objective is to efficiently control the lift of hydrofoil cross sections having closed cavities by using trailing edge flaps, optional leading edge flaps, and optional means for controlling gas flow rates.

Other objectives are to efficiently initiate cavities by introducing discontinuities to separate the water boundary layer in various ways, efficiently distribute the gas to each cavity, control the cavities, and separate adjacent cavities with different kinds of fences.

Still another objective is to minimize cavity drag on underwater surfaces by closing the cavities as smoothly as possible by minimizing the contact angle between the cavity and the surface. Another objective is to further minimize cavity drag by adding parallel ridges in the vicinity of cavity closure to reduce forward splash and thereby minimize gas entrainment out of the cavity.

Yet another objective is to use cavities to reduce the drag on all sides of ship hulls. Further objectives are covered in the description which includes the above and ongoing specification and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic representation of the side view of a low-drag, high-speed hydrofoil craft showing an above-water hull, a hydrofoil, support struts and a propeller.

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FIG. 2 shows a bottom view of the craft.

FIG. 3 is a front view of the craft.

FIG. 4 is a front view of a similar craft powered by shrouded air propellers.

FIG. 5 illustrates a hydrofoil with reverse sweep from that shown in Fig. 2.

FIG. 6 is a schematic cross section of a low drag hydrofoil with a tail flap, showing a cavity sensor, and two alternative closed cavities on each surface: a design cavity, and a slightly longer cavity.

FIG. 7 shows the same hydrofoil with the flap deflected.

FIG. 8 is a schematic detail of an alternative hydrofoil nose section comprising an angled plate.

FIG. 9 is a schematic detail of another alternative hydrofoil nose section comprising a perpendicular plate.

FIG. 10 is a schematic representation of a different kind of low drag hydrofoil that has a closed cavity on the upper surface, and a superventilated cavity on the lower surface.

FIG. 11 is a schematic detail of a wedge-shaped hydrofoil nose section with variable wedge angles.

FIG. 12 is a schematic detail of an alternative wedge-shaped hydrofoil nose section having a sliding block at each aft end to control cavity thicknesses.

FIG. 13 is a schematic detail of an angled-plate hydrofoil nose section with a variable plate angle.

FIG. 14 is a cross section of a nose region of a hydrofoil showing a means to duct gas from a cavity on one side into a cavity on the other side.

FIG. 15 is a cross section of a nose region of a hydrofoil showing flaps that cover gas ejection holes or slots.

FIG. 16 is a cross section at a strut-hydrofoil juncture showing how gas is delivered to different internal chambers in a hydrofoil.

FIG. 17 is a cross section of a hydrofoil showing methods for initiating cavities, moving gas from internal chambers into the cavities, removing gas from cavities, and for recycling the removed gas.

FIG. 18 is a similar cross section showing different ways to duct gas from a strut into internal ducts in a hydrofoil, and to move gas between different internal ducts within the hydrofoil.

FIG. 19 is a cross section of a hydrofoil showing how gas can be moved from several ducts in a strut into several ducts in a hydrofoil.

FIG. 20 is a schematic detail of a tail region of a hydrofoil showing a tab in a tail flap.

FIGS. 21A and B illustrate parallel ridges on a hydrofoil surface aligned with the water flow that are located in the desired cavity closure region.

FIG. 22 is a spanwise cross section of a hydrofoil surface showing four kinds of fences that can be used to separate adjacent gas cavities.

FIGS. 23A and B are side and end views of a swept, tapered strut that supports a hydrofoil, showing an upper superventilated region, a fence, a lower strut region with a closed cavity, and a bottom region that is fully wetted.

FIG. 24 is a cross section of the strut showing an optional nose flap used to deflect a cavity, a trailing edge flap, different internal ducts, and optional side wedges.

FIG. 25 is a schematic detail of a nose section of a strut showing how cavities are initiated, and how a nosepiece can be attached to the strut body.

FIG. 26 illustrates an alternative flat plate nose to initiate cavities.

FIG. 27 illustrates an elongated version of the nosepiece shown in Fig. 25.

FIG. 28 is a side view of a strut that is swept down and forward.

FIG. 29 is a front view of an angled strut.

FIG. 30 is a cross section of a strut showing how a bottom portion of the strut, and an attached hydrofoil, can be spring loaded to reduce craft motion.

FIG. 31 shows a propeller hub with a cross section of a superventilating propeller blade.

FIG. 32 is a similar view showing a propeller blade that has a closed gas cavity on its suction side, and an open, superventilated cavity on its lower side.

FIG. 33 is a similar view showing a propeller blade that has a closed gas cavity on each side.

FIG. 34 is a cross section of a pod that encloses an electric motor which drives a shrouded propeller.

FIG. 35 is a side view of a hydrofoil boat hull supported above water by struts attached to a primary swept v-hydrofoil, together with a bow lifting device comprising an inverted, swept v-foil that provides pitch and roll stability.

FIG. 36 is a front view of the boat.

FIG. 37 is a side view of an alternative bow lifting device comprising parallel, flexible planing plates.

FIG. 38 is a front view of an alternative primary v-hydrofoil wherein the ends of the hydrofoil are canted upward to pierce the water surface to provide roll stability.

FIG. 39 is a front view of the main hydrofoil wherein the aft support struts are angled to provide roll stability, and the bow lifting device is a surface piercing v-hydrofoil in front view.

FIG. 40 is a side view of the hydrofoil boat wherein the main v-hydrofoil is reversed in sweep wherein the tips of the hydrofoil are forward, and are canted upward to provide pitch and roll stability.

FIG. 41 is a side view of a hydrofoil boat hull supported above water by a strut attached to a lifting, swept v-hydrofoil, wherein part of the boat lift is provided by aerodynamic wing lift, and wherein the boat is stabilized in pitch and yaw by an aerodynamic tail.

FIG. 42 is a side view of a ship hull showing multiple closed cavities on side and bottom surfaces.

FIG. 43 is a horizontal cross section of the ship hull showing the side cavities.

FIG. 44 is a side view of a ship hull that is mostly submerged, and has closed cavities on the side, bottom and top surfaces.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In Figs. 1 and 2, the hull 2 of hydrofoil craft 1 is supported above water by forward strut 4 and two aft struts 5 which are attached to lifting v-hydrofoil 3. The propulsion system consists of engine 7 in each catamaran hull 6 that drives shaft 8 located in duct 9 of strut 5, thereby eliminating drag on the drive shaft. Shaft 8 enters gearbox 11 located inside pod 12 to drive propeller 13. Pre-spin vanes 14 rotate the water flow entering the propeller so that the water flow leaves the propeller without significant rotation, thereby increasing propeller efficiency. This hydrofoil and propulsion arrangement is equally applicable to monohulls, trimarans or other hull shapes, and applies to one or more support struts, engines and propulsors. Each strut can either be swept back, as shown, or unswept, or swept forward. Strut sweep reduces strut spray drag, and reduces strut side force in beam waves. Hydrofoil sweep reduces susceptibility to cavitation, and reduces craft vertical motion in waves. The sweep shown in Fig. 2 is around 70 degrees. Sweep of only 30 degrees is beneficial. Sweeps of 45 and 60 degrees are more beneficial. These beneficial

effects are not affected whether a hydrofoil is swept back or forward. With a leading edge sweep angle of 70 degrees, the included angle between leading edges is 40 degrees. With a sweep angle of 30 degrees, the included angle is 120 degrees. Sweep angles are measured from a direction perpendicular to the craft centerline. Hydrofoil chord distribution affects induced drag. Minimum induced drag occurs for an elliptic chord distribution. Longer chords are nearer the craft center, shorter chords are nearer the hydrofoil tips.

Rudder 10 in each aft strut 5 helps to steer the craft. Banking the craft into a turn by using flaps increases turn rate, and minimizes craft side force. Hinges 15 permit the hydrofoil to retract rearward and upward. Sonar device 16 helps to detect underwater obstacles that lie in the path of the craft, and can also serve to generate forward-projected sounds to frighten or urge sea animals away from the path of the craft.

Outboard trailing edge flaps 17 serve to control craft roll and pitch, and together with inboard flaps 18, serve to control craft height. Fences 19, wetted pods 12, and wetted region 20 serve as fences to separate adjacent spanwise cavities on the hydrofoil in the case where the hydrofoil is supplied with gas cavities to reduce drag. Projection 21 on the underside of hull 2 at the center helps to reduce forward strut height, and to cushion bow impacts when operating in large waves.

A sweptback v-hydrofoil that is placed at a small angle of attack can appear to have a small negative dihedral 22, or it can be designed for a negative dihedral; in either case, it will appear somewhat as shown in Fig. 3. Alternatively, for dynamic reasons in some cases, a v-hydrofoil might be designed with a positive dihedral 23, as shown in Fig. 4.

Calculations show that shrouded air propellers 24, such as shown in Fig. 4, can be as efficient as underwater propellers in some cases.

Fig. 5 illustrates a hydrofoil 25 whose sweep is reversed from that of hydrofoil 3 in Fig. 2. From the viewpoint of foil sweep theory, little difference exists whether a foil is swept forward or back.

The drag of a hydrofoil, such as the one shown on the craft in Figs. 1 and 2, can be greatly reduced by covering the majority of one or both surfaces with a closed gas cavity, as shown in Fig. 6. The wedge-like nosepiece 31 of hydrofoil 30 introduces a surface discontinuity 31A on an otherwise streamlined upper surface 34, and a surface discontinuity 31B on an otherwise streamlined lower surface 34 of the hydrofoil, that causes the water boundary layer to separate from each side of the nosepiece. By introducing gas into the wake region of separated flow lying behind the discontinuity, a gas cavity 32, 33 can be formed. The flow discontinuity can be a 90-degree downward angle or step in the surface, as shown, or it could be a smaller downward angle, to as little as around 10 degrees. The discontinuity can also be a protuberance from the surface, such as spanwise wedge with a blunt trailing edge, where a trailing edge step serves to separate the water boundary layer from the surface. Other kinds of discontinuities are shown in Figs. 12-14.

Theory shows that cavity drag is zero, if the cavity closes smoothly. In the real world, it is not possible to exactly smoothly close a cavity. However, it is possible to minimize the contact angle between a cavity and an underlying surface in the cavity closure region so that forward splash at cavity closure is minimized, thereby minimizing the gas entrainment rate, and thus minimizing the size of the wake, and cavity drag.

Fig. 6 shows two cavities on each hydrofoil surface 34, 35, a shorter cavity 32S, 33S that closes in desired closure regions 36 and 37, and a longer cavity 32L, 33L that closes at 38 and 39 behind the desired closure region. Note that the hydrofoil surface 34, 35 is convexly curved so that the closure angle of shorter cavity in each case is much smaller than the closure angle of the larger cavity. Because of the greater closure angle, more gas is entrained out of the larger cavities than out of the shorter cavities. Consequently, if the gas flow rate into each cavity is controlled so as to not exceed the rate needed to close the shorter cavity, then neither cavity can close behind the desired closure region because not enough gas will be available to further extend the cavity. To determine where a cavity closes, cavity sensors 40 can be used to sense cavity length.

The shape of a gas cavity depends upon the cavity number K=(Po-Pc)/q, where Po is static depth pressure, Pc is cavity pressure, and q is the dynamic water pressure, where q is the speed squared times half the mass density of water. If K is small, the cavity is long and thin, and if K is large, the cavity is short and thick. In two-dimensional flow, K=2T/C where T=cavity thickness and C= cavity length; the cavity shape is an ellipse. As used throughout this patent, the word "gas" means any kind of gas, including air.

A tail flap 29 is shown in Fig. 6 in its neutral position, and is shown deflected in Fig. 7. Note that the location of the closure points, 42 and 43, for the longer cavity on each surface has not appreciably changed, indicating that the flap can be deflected without risk of the longer cavities lengthening beyond the trailing edge, especially if the flap is long enough. If necessary, a flap chord can be increased when the flap is deflected. Placing a concave surface just ahead of the trailing edge on each side of the flap will increase the cavity closure angle in the region ahead of the trailing edge to help to ensure that the longer cavities will not close behind the trailing edge.

A variety of nosepiece shapes can be used to initiate the cavities, such as angled nosepiece 44 placed on the lower front side of the hydrofoil in Fig. 8 to start cavities at discontinuities 45 and 46, or nosepiece 47 placed perpendicular to the flow in Fig. 9. Such nosepieces can be placed at any angle greater than about five degrees to the oncoming water flow. The nosepiece can be curved either way, and can include changes in angle. Nosepiece 47 can instead be v-shaped, or cup-shaped, wherein the upper and lower edges lie ahead of the center section.

The special hydrofoil shape in Fig. 10 shows promise for even-greater frictional drag reduction because its only wetted surface areas are the lower surface of the nosepiece 44 and the upper surface of the trailing

edge flap. Here, the upper surface is covered with closed cavity 32, and the lower surface is covered with an open, superventilated cavity 48. The two cavities close behind the trailing edge at 49. This hydrofoil design should have very low frictional drag if the cavity merger angle at 49 is made small.

The shape of a wetted hydrofoil nosepiece can be varied to change upper and lower cavity shapes, assist in controlling lift, and to reduce drag. For example, the angles of the upper and lower surfaces of wedge-shaped, flexible plate 58 can be independently controlled, as shown in Fig. 11, by changing the length of actuator 60 which is attached between rigid hydrofoil center plate 55 and rigid nose plate 59 to deflect the flexible v-plates 56 and 58 either outward or inward. The lower part 57 of the nosepiece can be controlled similarly.

Another way to change nosepiece shape is shown in Fig. 12 where plate 61 is moved vertically relative to nosepiece 31 in order to deflect cavity 32.

Still another way to change nosepiece shape is shown in Fig. 13 where plate 44 is rotated about axis 62 to deflect upper and lower cavities 32 and 33.

Because cavity number K increases as speed reduces, cavities tend to be shorter and thicker at lower speeds. Therefore, to reduce frictional drag at lower speeds, it is necessary to change cavity shape by either changing hydrofoil geometry, hydrofoil angle of attack, gas flow rates, cavity pressures, or combinations thereof. Various ways of changing hydrofoil geometry and hydrofoil pitch or angle of attack have been discussed. Typically, for a given hydrofoil geometry, a change in gas flow rate will provide an accompanying change in cavity pressure and shape. Thus, the gas source pressures and flow rates must be adequate to supply gas to the cavities under all of the desired operating conditions.

In most hydrofoil designs, the cavity pressure on the upper surface is less than atmospheric pressure, in which case the upper cavity gas can be air that is drawn from the atmosphere without using an air pump. If the upper cavity pressure is low enough, then a turbine can be placed in the associated air duct to generate power. Typically, the pressure on the lower surface of a hydrofoil is greater than atmospheric, in which case the gas, such as air, must be pressurized using a pump. However, in some cases, hydrofoil speed and geometry is such that the pressure on the lower surface of a hydrofoil, although greater than the pressure on the upper surface, can be made less than atmospheric pressure, in which case, no pump is needed and atmospheric air can be used.

For all lifting hydrofoils, the lower cavity must be at a higher pressure than the upper cavity. Consequently, there may be design cases where the simplest and best solution is to supply gas only to the lower cavity, and then duct some of the gas into the upper cavity. One such way is shown in Fig. 14 where gas from a lower cavity is passed through duct 63 to an upper cavity using orifices 64 and/or 65 to meter, or

restrict, the gas flow rate. These orifices, restrictors, or limiters could be valves, or ducts 63 could be made small enough to act as a restrictor, or limiter, to meter the gas flow rate without using valves or orifices.

It may be desirable to keep water out of the hydrofoil gas ducts. Fig. 15 shows flaps 68 that are used to cover gas ejection holes, or gas releasers, from hydrofoil ducts 69 and 70 through upper hydrofoil plate 66, and lower hydrofoil plate 67, wherein the flaps close the holes when no gas is ejected, but spring open when gas is released. Alternatively, one-way valves can be used instead of flaps.

In some cases, it is desirable to replace nosepieces, including the case where a nosepiece is damaged. The various kinds of nosepieces shown in Figs. 11-14 can be attached by various well-known methods to permit them to be removable.

Fig. 16 shows how gas enters hydrofoil ducts 69 and 70 from strut ducts 71 and 73, which act as gas sources, at a strut/hydrofoil juncture. Ducts 71 and 73 are more typically placed one ahead of the other in the plane of the strut rather than as side-by-side, as shown for clarity in the figure.

The hydrofoil cross section in Fig. 17 again shows strut ducts 71 and 73 to bring gas into hydrofoil duct 69 for ejection into upper surface cavities, and into duct 70 for ejection into lower surface cavities. In this case, valves or holes 78 and 79 meter some of the gas into adjacent spanwise ducts for distribution to other cavities located at other spanwise stations along the hydrofoil span. The gas passes through restrictor permeable walls 72 and 74 at the forward ends of the hydrofoil ducts, through slots at the front end of the upper and lower hydrofoil plates, and into the upper and lower cavities. The upper and lower surfaces of the hydrofoil are said to be substantially, or essentially, continuous in spite of the small slot aft of the nosepiece through which gas is ejected. To provide greater strength, if needed, the hydrofoil can be made solid in the mid and aft section, as shown in Fig. 17. If it is desired to remove gas from a hydrofoil cavity on one or both sides, and recycle it, then a suction inlet and gas pump, such as 75, 76, can be installed where the gas is returned by line 77 to gas duct 69 for recycling.

Another way to distribute gas to different cavities located on the upper and lower surfaces of a hydrofoil is shown in Fig. 18. Gas for the upper surface cavities enters from strut duct 71 into hydrofoil duct 80 where it passes through valves 82 into separated forward spanwise ducts 69, and from there through restrictor holes in wall 72 into separated spanwise cavities located along the upper surface of the hydrofoil. Gas for the lower surface cavities enters from strut duct 73 into hydrofoil duct 83 where it passes through valves 85 into separated rearward and forward spanwise ducts 86, 70, and through holes in walls 87 and 74 into separated spanwise cavities located along the lower surface of the hydrofoil.

Still another way to distribute gas into cavities is shown in Fig. 19. Gas for one upper surface cavity enters from duct 71 into an upper hydrofoil duct where it passes forward through holes in wall 72 into the cavity, while gas for a second upper surface cavity enters from duct 90 into a different upper hydrofoil duct

where it passes forward through different holes in walls 92 and 72, while gas for a third upper surface cavity enters from duct 94 into a still different upper hydrofoil duct where it passes forward through still different holes in walls 96, 92 and 72. Each of the three hydrofoil ducts is sealed spanwise to prevent gas from being ejected into more than one cavity. Similarly, gas for the lower surface cavities enters the hydrofoil through ducts 73, 91 and 95, and passes through different holes in walls 74, 93 and 97.

As seen from Figs. 14, 15, and 17-19, many different ways, and combinations of ways, exist for gas to be moved from strut ducts into hydrofoil cavities.

To reduce the torque needed to deflect a tail flap, such as flap 39 in Fig. 20, a section of the flap, such as tab 100, can be pivoted about axis 101.

As mentioned earlier, some cavity drag will occur at cavity closure due to forward splash and air entrainment. To minimize cavity drag, small parallel ridges 105, as shown in side view in Fig. 21A, and as shown in cross sections A-A in Fig. 21B, can be placed in line with the water flow in the region of cavity closure to reduce splash and air entrainment. The ridges serve to direct the splash sideward and rearward, instead of directly forward, thus reducing disturbances at cavity closure, and thereby reducing air entrainment and drag. The ridges can be saw-shaped as in 106, or u-shaped as in 107, but should be aligned to within 30 degrees with the local water flow direction. Other ridge shape cross sections can be used, and the height of the ridges can taper down at each end.

Whenever gas cavities are formed on hydrofoils, struts or other surfaces, the pressures in adjacent cavities can be different, in which case the cavities should be separated by some type of a fence. Fig. 22 shows four types of fences, looking in the direction of water flow. Fence 110 is a wetted region on the underwater surface, and if sufficiently wide, serves to separate adjacent cavities having different pressures. A more common type of fence is thin plate 111 whose height must exceed the cavity height, and whose length must exceed the cavity length. Still another type of fence is water jet 112 comprising a sheet of water directed outward from the surface that has sufficient momentum to reach the cavity walls before being curved away from the cavity walls due to the pressure difference between cavities. Another type of fence is gas jet 113, which is similar to the water jet fence in that it also requires sufficient momentum to reach the cavity walls before being curved away from the cavity walls.

Strut 120, shown in Fig. 23A and B, is superventilated 117 in an upper region 118 of the strut on both sides down to fence 124, starting at the ends of nosepiece 121 and ending along cavity closure line 123. Closure of an open cavity typically causes a plume of water to be raised above water surface 130, resulting in a bubbly wake whose loss in energy represents cavity drag. If strut 120 is sufficiently thin, then cavity drag can be much less than the frictional drag of a wetted strut. Below a certain depth, strut drag can be minimized in a lower region 119 by forming cavity 127 that closes along line 126. Typically, the pressure in

cavity 127 is less than atmospheric, so fence 124 is needed to separate this cavity 127 from the upper cavity 123. Air for the closed cavity 127 can be introduced through holes 125 from a duct inside the strut, through spanwise slots lying behind nosepiece 121, or through holes 124A in fence 124 shown in Fig. 23B. In some cases, the closed cavity pressure can be made atmospheric, so fence 124 is not needed. To separate cavity 127 from a cavity on the upper surface of hydrofoil 129, a bottom region 128 of the strut is shown fully wetted to act as a fence between these cavities.

Fig. 24 is a cross section of the upper region of the strut shown in Figs. 23A and B. Tail flap 122 is used to control strut side force for turning. The tail flap can either be deflected in the normal steady-state manner out a desired flap angle, or it can be deflected out to a fixed angle and back at a moderate frequency, sometimes called a "bang-bang" control. Optional nose flap 135 can be deflected outward to move cavity 136 outward, if needed, to keep the cavity from wetting the strut under certain operating conditions. Alternatively, outward steps 138 can be placed on the strut sides to deflect cavity 123 away from the strut at lower speeds, or in waves, if needed.

Various nose sections 121, 140 and 142, and ways of attaching the nose sections to struts, are shown in Figs. 24-27. Center plate 140 can either be used to support a nosepiece, as in Figs. 25 and 27, or it can be the nosepiece itself, as in Fig. 26. The upper region of the strut can be ventilated directly from the atmosphere, or additional air can be ejected through the strut to help ventilate the cavity, such as by ejecting air through a permeable member 141.

A ventilated strut can also be swept forward, such as strut 145 in Fig. 28, or angled to the vertical, such as strut 146 in Fig. 29. Also, a lower portion 148 of strut 120 can be spring loaded by means of spring 147 shown in Fig. 30 to permit attached hydrofoil 129 to move vertically relative to the craft in order to reduce craft motion in waves. If the hydrofoil does not provide the necessary damping, a damping device can be added in parallel with the spring means. Alternatively, the entire strut and hydrofoil system can be spring loaded to reduce motion in waves.

The drag of underwater propeller blades or rotors can be reduced by using gas cavities, such as by superventilating 151S the upper, or forward, surface 151A of blade 151, attached to hub 150, as shown in Fig. 31. A very efficient, new way to reduce drag on a propeller or rotor blade is to superventilate 152S the lower, or rearward, surface 152B of a blade 152, and form a closed cavity 152C on the upper, or forward, surface152A, as shown by blade 152 in Fig. 32. Another very efficient way to reduce propeller frictional drag is to form closed cavities 153C, 153D on each side 153A, 153B of each blade, such as blade 153 shown in Fig. 33.

Instead of driving a propulsor with shafting, an electric motor 155 can be housed in pod 154 shown in Fig. 34 that drives a propulsor such as shrouded propeller 156, where shroud 157 is supported by vanes

158. By cambering the shroud outward, such as in a pumpjet, the water pressure inside the shroud can be increased above depth pressure, thus reducing cavitation on the rotor blades.

A problem associated with craft having fully submerged hydrofoils, such as the hydrofoil craft design shown in Fig. 1, is that an automatic control system is needed to dynamically stabilize the craft. A bow lifter, such as a surface piercing, inverted, sweptback v-hydrofoil 163, as shown in Figs. 35 and 36, can be attached to hull 160 of hydrofoil boat 162 to stabilize the boat in heave, pitch and roll. For example, if boat 162 were lowered in the water, then the lift of bow hydrofoil 163 would increase, the bow would rise, and hydrofoil 3 would also rise due to the increased angle of attack. Similarly, if the boat pitch suddenly increased, then hydrofoil 3 would rise to bring pitch back to normal. Although boat 162 is shown with an outboard drive 161, the same type of bow hydrofoil 163 may be used with a larger boat or ship. In case of a sudden roll, Fig. 36 shows that one side of bow hydrofoil 163 would lower, and the other side would rise, causing a hydrodynamic moment that restores the boat angle back to level. A different type of bow lifter is a series of flexible parallel planing plates 164, shown in Fig. 37 to stabilize a craft in heave and pitch, and also roll if the span is large enough. Many other kinds of bow lifters can be used, including ski-like lifters that look much like the lifter shown in Fig. 37; two side-by-side skis can provide roll stability. The bow lifter could also be shaped like a cut-off bow of a boat placed below the hull bow, such as shown in Fig. 2; two such cut-off bows can provide roll stability.

Another way to stabilize a hydrofoil boat in roll is to angle the ends of hydrofoil 3 upward to pierce the water surface, as shown in Fig. 38 by a hydrofoil with midsection 165, and lifting end sections 167. In this case, fences 166 are needed to separate adjacent cavities, especially if hydrofoil section 167 is outfitted with different kinds of cavities above fence 166. Since the boat is now stabilized in roll, bow hydrofoil 163 could be replaced by bow hydrofoil 168 shown in Fig. 39, which is a surface piercing v-hydrofoil with positive dihedral. Hydrofoil 168 would provide the needed heave and pitch stability.

Also shown in Fig. 39, are tip hydrofoils 169 for reducing the induced drag of the hydrofoil. These tip hydrofoils serve to increase the aspect ratio of the main hydrofoil by increasing its span and changing the flow pattern near each end. The tip hydrofoils can be angled up or down relative to the main hydrofoil, and can be either fully wetted or have a closed cavity on one or both surfaces. The tip hydrofoils can also be placed at an angle of attack to the flow in order to generate a vortex that is opposite in direction to the usual tip vortex generated near each end of a main hydrofoil to reduce induced drag.

Another way to stabilize a hydrofoil boat is to retain hydrofoil 3, but support it with aft angled struts 5A designed to provide lift and stabilize the boat in roll. Struts 5A would then become surface piercing hydrofoils.

Still another version of a hydrofoil boat is to reverse hydrofoil 3A so it is swept forward, and angle ends 5B of hydrofoil 3A upward, as shown in Fig. 40 to stabilize the boat in heave, pitch and roll. Aft, single strut 4A now supports the vee tip 169 of hydrofoil 3A. Strut 4A could instead be swept down and back.

There are a wide variety of ways to stabilize a hydrofoil boat in heave, pitch and roll, including the addition of bow lifting means, and angling sections of hydrofoil 3 and angling struts, any of which can be wetted, or vented with cavities to reduce drag.

To improve performance on high speed hydrofoil boats or ships, aerodynamic lift can be used to supplement hydrodynamic lift. For example, wing 170 in Fig. 41 can be added to augment the lift of hydrofoil 3 to support hull 160 above water. Propeller 174 is shown attached to canted shaft 173 to drive the boat. Alternatively, outboard motors can be used, or an air propulsion system. Vertical air stabilizer 172, and horizontal air stabilizer 171 can provide aerodynamic stability in pitch and yaw. Wing 170, due to its closeness to the water surface, and the resulting ground effect, can provide heave and pitch stability. Alternatively, aerodynamic control surfaces can be used to control heave, pitch and roll. Also, hull 160 can be shaped to augment lift, instead of wing 170, especially if the hull is a catamaran or a trimaran where the cross structure can be shaped to generate lift.

In the various hydrofoil craft designs shown herein, the hull does not have to be supported entirely above water; instead, the hull could remain in contact with the water, in which case hull lift would be augmented by hydrofoil lift.

Air cavities can be used in a wide variety of ways to reduce drag on underwater surfaces. Figs 42 and 43 illustrate a way to use closed air cavities to reduce drag on the sides and bottom of surface ship 180. A discontinuity or step 182 at the end on each side of nosepiece 181 forms a side cavity 183. A series of multiple steps 184 are placed downstream to form additional closed cavities 185 that terminate by wetted tailpiece 186. Frictional drag on the bottom surface 190 is minimized similarly, starting with nose step 187 and closed cavity 187C, followed by multiple steps 187 and cavities 187C, until reaching wetted tailpiece 186. The surface 192 underlying each cavity is curved somewhat like the cavity surface 194, and is designed to minimize the contact angle 196 at the end of each cavity. A fence is needed between each side cavity and each adjacent bottom cavity. The cavity lengths on the bottom are not necessarily the same as the lengths of the side cavities. Also, the height and angle of the various surfaces ahead of each step tend to vary with depth, and with downstream station. Typically, cavities are longer and thinner near the surface than near the bottom. At the very surface, the side cavity shapes tend to be parabolic, so here the cavities tend not to close; however, as depth increases, the side cavities will close. Because of this depth effect, steps 187 tend to increase in height toward the bottom. Since cavity shapes change with speed, step heights can either vary

in height with speed, or step heights can be designed for a specific speed, and more steps added for use at lower speeds.

The hull shown in Fig. 44 is similar to that in Fig. 42, except it is essentially under underwater, so it has an upper surface 198 that is also covered with closed cavities 189, formed by a series of steps 188 to generate a series of cavities 189 to reduce drag. Nose and tail sections, 181 and 186, pierce the surface to provide air for the cavities, and provide heave and pitch stability; roll stability is achieved by placing the center of gravity below the center of buoyancy.

In the many embodiments described herein, each can be used with others, or parts of each can be combined with parts of others, to enhance efficiency or performance. Also, automatic control systems, in conjunction with a variety of sensors, can be used to control any moving part in order to dynamically control craft motion, or to control cavity effectiveness.

While the invention has been described with reference to specific embodiments, modifications and variations of the invention may be constructed without departing from the scope of the invention, which is defined in the following claims.

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